



## Proceedings of the Eurosensors XXIII conference

## Fault detection and isolation enhancement of an aircraft attitude and heading reference system based on MEMS inertial sensors

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**Abstract**

The process of enriching a multisensor avionic strap-down attitude estimation unit with fault detection and isolation (FDI) capabilities is presented. Compact solid-state sensors are integrated in an autonomous emergency guidance system for aircrafts. Optimal attitude estimate is provided by a 9-state extended Kalman filter for fusion of complementary inertial data. Observer-based residual generation can be consequently added with negligible computational overhead. On-line FDI of the different sensors is analyzed and achieved with minimal hardware and software modifications. The proposed detection scheme combines different approaches: physical redundancy (accelerometers), injection of spectrally-decoupled test signals (magnetic sensors) and analytical redundancy (gyros).

*Keywords:* Fault detection; Analytical redundancy; Inertial MEMS; Attitude estimate; Kalman filter; Data fusion

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**1. Introduction**

The employment of ultra compact attitude estimation systems based on low-cost MEMS inertial sensors is becoming ubiquitous in various application fields (manned and unmanned terrestrial, underwater and aerial vehicles, robots and human body tracking). We present a FDI strategy [1] that can be adopted in any system based on triads of off-the-shelf MEMS accelerometers (providing direct gravimetric attitude estimate) and gyros (providing short time angular rates), regardless the absence of built-in self test options in the sensors. This diagnostic feature plays a fundamental role in safety critical applications, in particular for avionic instrumentation, where it is often implemented at whole aircraft level [2], requiring specific aerodynamic models and signals collected from different units. On the contrary, our approach encompass combined hardware and algorithmic solutions at the very front-end of low-cost sensors, suitable for such totally autonomous application. Analytical redundancy [3] has been adopted relying on the intrinsic kinematics relating gyros and accelerometers. It has been developed to enhance the diagnostic capabilities of a custom-designed attitude and heading reference system [4] for an avionic emergency stand-by display, shown in Fig. 1(a). It represents an emergency aircraft navigation system that provides basic flight parameters, namely heading, attitude and air data, measured through independent dedicated solid-state sensors.

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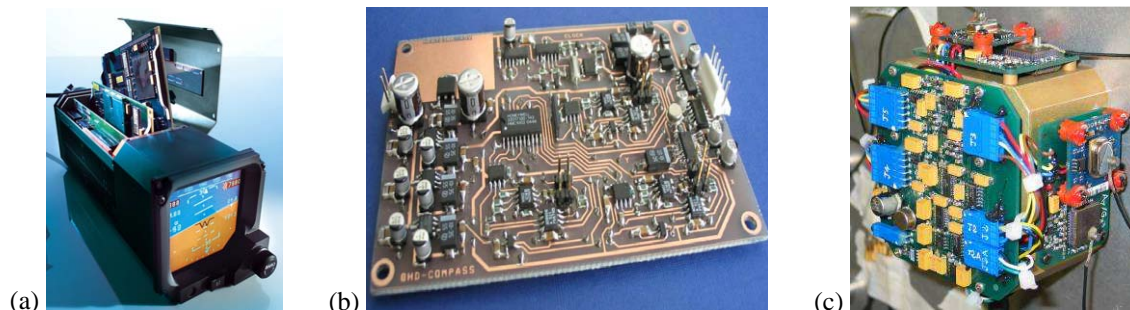


Fig. 1. (a) Emergency, autonomous, compact stand-by display (3'' cockpit instrument) where the compass prototype (b) and the cluster of inertial MEMS attitude sensors (c) will be incorporated.

## 2. Sensors fault analysis

The design of the fault monitors begins with a systematic analysis and classification of all the faults that may affect the sensors, along with their effect on the output estimates. Due to the coupling among the differential equations relating attitude sensors kinematics, except for accelerometer  $x$  affecting only the pitch angle, all other single faults have a detrimental impact on both roll and pitch estimates.

We assumed that the result of any kind of fault produces a constant signal at the sensor output, stuck to a constant level irrespective of the input measurand variations. The values with the highest probability are the saturation to the power supply rails and the drop to zero. These failures may be due to causes both external and internal to the MEMS sensors, such as interconnection failure (power supply or output wire disconnection), internal breakdown of the silicon moving parts, of suspension beams, or of the transducer circuitry. Electromagnetic and mechanical stress and shocks may also be a threat, although the sensors have been fully characterized to comply with vibrational and electromagnetic standard avionic certification requirements.

All other types of unexpected signal patterns, such as extra noise, pulses and scale-factor errors are considered transient phenomena, most commonly due to component aging, that will eventually lead to a definitive constant breakdown. As a future development, pattern recognition and spectral analysis may be applied to detect such waveforms, for earlier diagnostics of incipient faults.

We can concentrate only on the sensors as the acquisition chain (comprising analog signal conditioning stages and analog-to-digital converters) is monitored by periodically connecting the input through a multiplexer to a known reference voltage.

## 3. Implementation of the FDI strategy

### 3.1. Compass unit

When inside the sensor, along with the transducer, it is integrated also an actuator, the most natural fault detection approach is to use it for injecting a known test signal. This is the case of the triad of magnetoresistive sensors constituting the magnetometer (Fig. 1(b)). In fact, inside the sensor package an auxiliary coil is available for the generation of a local field, superimposed to the external field and aligned with the sensitivity axis. This inductor is already employed to operate in a closed-loop configuration, for improved thermal stability [4]. Furthermore, in order to cancel the sensor offset, its response is modulated by a 1kHz carrier and the offset-free signal is synchronously demodulated with a lock-in filter. Thus, as illustrated in Fig. 2(a), a test sinusoid, spectrally decoupled from the input signal, can be injected and measured at the output, before the signal is fed to the lock-in stage. A frequency in the range 10kHz-100kHz is still in the sensor bandwidth and sufficiently far from the modulation carrier to allow proper filtering. By adopting this approach, requiring the addition of a few hardware modules (oscillator and demodulator), all the components (sensor, inductor and modulator) are monitored.

After the identification of a fault, the damaged magnetoresistive sensor is isolated: a warning alarm ("corrupt heading estimate") is displayed to the pilot and the information is stored for post-flight maintenance purposes.

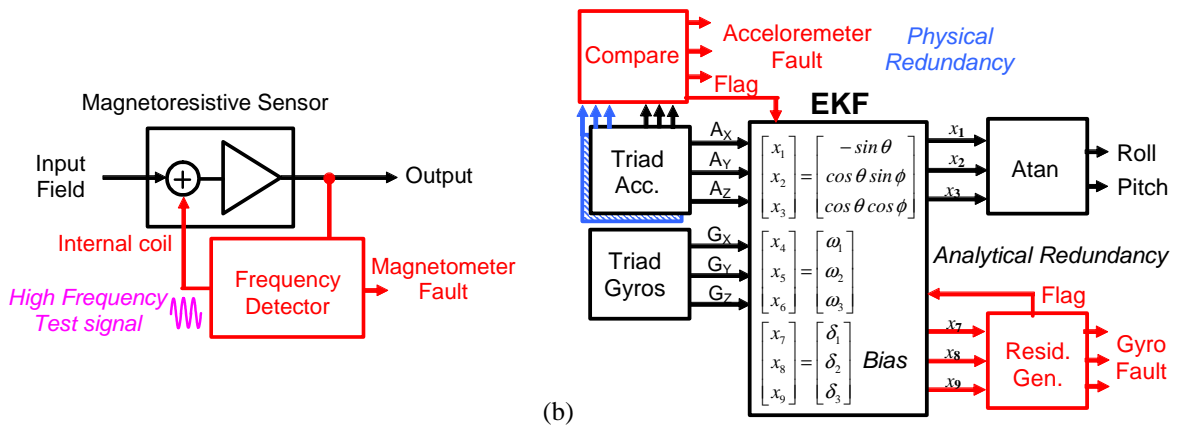


Fig. 2. (a) Injection of a sinusoidal test signal (10–100kHz) via an auxiliary inductor. (b) Data fusion: 9-state extended Kalman filter (EKF) based on direction cosine attitude parameterization, tracking gyro biases and adaptively reconfigured, upon fault detection flag assertion.

### 3.2. Attitude unit

Optimal attitude estimate is obtained fusing data from complementary inertial sources: accelerometers and gyros, providing long-term, low-frequency absolute gravimetric attitude estimate (affected by maneuver-induced accelerations) and short-term angular rates to be integrated (divergent error), respectively. The orthogonal triad of accelerometers is already duplex redundant, as two counter-aligned accelerometers are present on each axis, for a differential readout, that allows improved offset thermal stability [4]. Thus, instead of the actual hardware differential configuration, the two signals must be separately acquired and a mismatch detector is added, providing immediate fault identification.

On the other hand, due to cost and volume constraints, gyros (visible in Fig. 1(c)) cannot rely on physical redundancy. Instead, thanks to the presence of an *observer*, the data-blending Kalman filter, *analytical redundancy* can be easily implemented with negligible computation overhead. A precision/computational load trade-off sets the number of state variables: 3 direction cosines (singularity-free attitude parameterization, whose propagation equations are non-linear, requiring a linearized “extended” filter, but maintaining a linear sensitivity matrix in a “tight-coupling” fashion), 3 angular rates and 3 gyros biases. As the gyro biases track the constant components of the sensor signals, they directly reflect the saturation to an erroneous constant level and can be employed as residuals [5]. Thus the gyros biases are threshold detected by the a robust decision making block and single faults are identified.

## 4. Results and discussion

The threshold has been initially set to a constant value equal to  $3\sigma$  (63°/s), where  $\sigma$  is the nominal standard deviation of the gyro bias. As illustrated in Fig. 3(a), the saturation of gyro  $x$  to the positive power supply rail is simulated at  $t = 30$ s and the threshold on the gyro  $x$  bias is passed after 180ms (Fig. 3(b)). The effect on the uncorrected roll estimate is a sharp spike due to the anomalous abrupt variation of the gyro bias and eventually a 20% overshoot in response to roll step variations, performed at the maximum angular rate (400°/s). An *observability* issue is of course involved in the detection of a zero output fault: the fault is detected when the sensor is physically stimulated by an aircraft maneuver.

Unlike the heading unit, upon fault identification and isolation, the attitude system is reconfigured. In fact, thanks to the activation of a flag, the blending parameters are *adaptively re-tuned* so that the attitude estimation function is preserved, though its performances are degraded with respect to target specifications (0.1° resolution,  $\pm 0.5^\circ$  static and  $\pm 2^\circ$  dynamic accuracy). An example of the advantage of the adaptive reconfiguration is shown in Fig. 4(a) where the roll estimate is degraded after a fault of accelerometer  $y$ : without any flag assertion, the dynamic response is worsened and the static error reaches 45°, while with the reconfiguration the static error is limited to 4° and the dynamic performances remain unaltered.

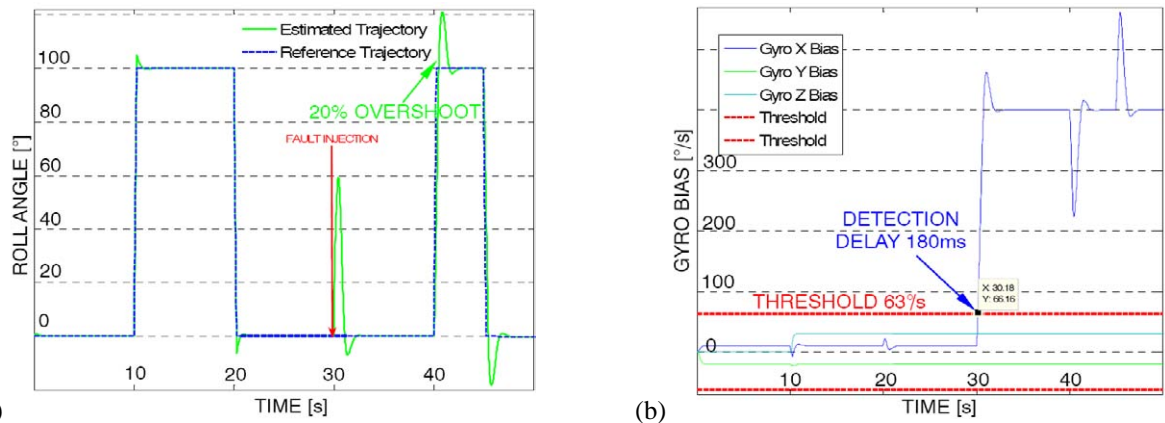


Fig. 3. Matlab simulation of a gyro  $x$  saturation at power supply rail ( $t=30s$ ): the dynamic response of roll angle is severely degraded by a 20% overshoot (a). The residuals (gyro biases) are tracked by the Kalman observer (b) so that the fault is threshold detected ( $63^\circ/s$ ) in 180ms.

To summarize, we can remark how the complementary data fusion approach intrinsically provides a powerful platform for fault detection, as the two data sources are constantly compared and cross-checked by the observer. Discrepancies are detected in few iteration cycles (tens of ms in the embedded implementation). Furthermore, the system can maintain its functionalities by adaptively modifying the covariance matrix, quantifying the statistical confidence associated to the new measurements. Gyro faults worsen the dynamic response while a gravimetric failure deteriorates the static accuracy. Thus, the complete failure of the attitude unit occurs only after the cascade of two subsequent faults, affecting both complementary sensor clusters, as shown in Fig. 4(b) where a fault of accelerometer  $y$  is followed by a gyro  $x$  fault, resulting in an roll estimate diverging error.

## Acknowledgements

The support of Fondazione Foresio is gratefully acknowledged, as well as inspiration by Prof. Giorgio Rizzoni.

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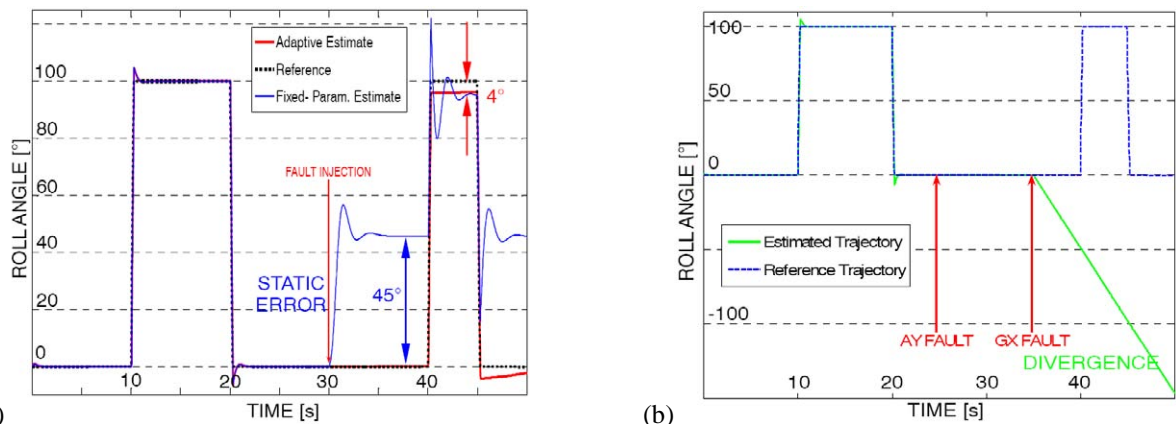


Fig. 4. (a) Improvement of the adaptive filter tuning ( $4^\circ$  static error) after accelerometer  $y$  fault, compared with fixed parameter estimate that produces  $45^\circ$  error and overshooting. (b) Fatal combination of multiple faults: accelerometer  $y$  and gyro  $x$  cause the divergence of roll estimate.